Assessment of atmospheric moisture harvesting by direct cooling

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article info

abstract

The enormous amount of water vapor present in the atmosphere may serve as a potential water resource. An index is proposed for assessing the feasibility and energy requirements of atmospheric moisture harvesting by a direct cooling process. A climate-based analysis of different locations reveals the global potential of this process. We demonstrate that the Moisture Harvesting Index (MHI) can be used for assessing the energy requirements of atmospheric moisture harvesting. The efficiency of atmospheric moisture harvesting is highly weather and climate dependent, with the smallest estimated energy requirement found at the tropical regions of the Philippines (0.23 kW/L). Less favorable locations have much higher energy demands for the operation of an atmospheric moisture harvesting device. In such locations, using the MHI to select the optimal operation time periods (during the day and the year) can reduce the specific energy requirements of the process dramatically. Still, using current technology the energy requirement of atmospheric moisture harvesting by a direct air cooling process is significantly higher than of desalination by reverse osmosis.

1. Introduction

The world's growing population puts severe demands on fresh water production and supply, and in many areas existing water resources are already overstretched (Kummu et al., 2010). Specifically, existing potable water resources are being depleted in many areas due to climate changes (in terms of both precipitation and evapotranspiration) and as a result of fast urbanization, exponential population growth and lack of (or inadequate) treatment of wastewater. Actually, by 2025 two thirds of the worldwide population is expected to live in regions with water scarcity (Macedonio et al., 2012). Hence, alternative water sources and innovative technologies for drinking water production are sought. Clearly, the availability of an immense amount of ocean water can be utilized (mainly in coastline regions) for seawater desalination. The latter is performed mostly by a reverse osmosis (RO) membrane technology, which became cost-effective in the last decade and is therefore practiced intensively (Semiat, 2008). However, although RO seawater desalination is among the most promising alternative water production technologies, it is not applicable in countries and regions that do not have access to the sea or to underground brackish water. Moreover, transportation of desalinated water from coastline areas to inner continental regions requires large investments in infrastructure, and have high operation energy demands. In contrast, atmospheric water vapor is a potential source of a plentiful amount of fresh water that is accessible everywhere, yet the process is not cost-effective nowadays. The atmosphere contains about 13,000 km³ of fresh water, 98% of

which is vapor and only 2% is in a liquid phase (cloud droplets, fog). This amount is comparable to all the surface and underground freshwater, excluding ice and glaciers (Beysens and Milimouk, 2000). Liquid water is easier to capture, as naturally done by vegetation and animals (Andrews et al., 2011; Malik et al., 2014; Parker and Lawrence, 2001). Man-made fog traps have been tested over the last few decades to some extent (Klemm et al., 2012). However, frequent and predictive fog events occur only in very specific places that enjoy favorable conditions (Domen et al., 2014), thus, on a large scale it is even less accessible than seawater. The common way for extracting the atmospheric humidity is by condensing the vapor, i.e. the moist air is cooled to a temperature below its dew point following contact with a cold surface. This process involves a significant latent heat release (~2500 kJ/kg$_w$) as well as sensible heat interaction between the air and the surface. Hence, the condensation process is limited by the rate of heat loss from the surface, which is necessary to keep its temperature bellow the dew point. Radiative cooling towards the night sky drives natural atmospheric moisture extraction via the formation of dew on surfaces (Muselli et al., 2006; Nikolayev et al., 1996; Sharan, 2013). The maximum expected yield of radiative dew harvesting is ~0.8 L/(m² d) (Beysens et al., 2013) but empirical studies of passive dew capturing reveal much lower and varying water yield (Beysens et al., 2005; Guan et al., 2014; Jacobs et al., 2002, 2008; Nilsson, 1996). In general, the process is limited by the rate of radiative heat exchange, the weather and the surface properties (Beysens, 2016). In particular, weather conditions dictate the ratio of latent to sensible heat exchange between the surface and the air. When the dew point temperature, T_d, is much lower than the air temperature, T_a, most of radiative cooling is consumed by a sensible heat exchange and the dew yield may drop to zero. Indeed, if

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$T_a - T_d$ N10 K it is unlikely to get any significant dew yield (Beysens, 2016). Hence, passive dew harvesting can be only a supplementary water source in regions with favorable conditions (Lekouch et al., 2011; Sharan, 2002).

Another possible approach to harvest atmospheric humidity is by active cooling of the ambient air, using an electric compression-expansion device (Wahlgren, 2001, 2014). Whereas the energy investment liberates the process from the limited passive radiative cooling rate, the efficiency of the process is still highly dependent on the meteorological conditions. Several such atmospheric moisture harvesting (AMH) systems are currently available in the market, mostly for emergency use and when relatively small amounts of freshwater are required. In this study, we present a method for estimating the energy requirement, the efficiency, and the water production rate of water generators (i.e. atmospheric moisture harvesting by direct air cooling devices), accounting for site-specific climate and meteorological conditions. Moreover, the moisture harvesting potential can be used for the selection of optimal time-periods for an on-off operation mode, which can increase the overall moisture harvesting efficiency by avoiding operation when the ambient air conditions are highly unfavorable. The suitability of climate conditions for AMH by direct electrical cooling is assessed by a new index, the Moisture Harvesting Index (MHI), which reflects the ratio of the energy invested in the desired water condensation process to the total energy invested in the cooling of the condensable as well as the incondensable gasses in the air bulk. The use of the MHI for estimating water production and its energy requirements will be demonstrated.

2. Moisture Harvesting Index

The idea behind AMH by direct cooling is simple: ambient air meets a cold surface and the temperature difference facilitates heat transfer from the air to the surface, resulting in temperature decrease of the air that is in close proximity to the surface, and condensation of the vapor that exceeds the moisture saturation capacity of the chilled air. The total heat interaction of the air is the sum of the sensible heat, associated with the temperature change of the air and the vapor, and the latent heat, associated with the enthalpy of condensation (ASHRAE, 2013),

$$q_{tot} = q_s + q_l; \qquad (1)$$

where q_{tot} [kJ/kg_a] is the total heat interaction, q_s [kJ/kg_a] is the sensible heat interaction and q_l [kJ/kg_a] is the latent heat of condensation. For practical reasons, all these interactions are defined per one kg of dry air (denoted by kg_a), since the dry air mass remains constant throughout the process.

In conventional air conditioning systems, the desired product is cooled air, and any latent heat that results from humidity condensation overburden the cooling load. A sensible heat ratio (SHR) is commonly used by heating, ventilation and air conditioning (HVAC) engineers (Pita, 1989) to determine the ratio of the sensible to total heat interactions, which depends on the conditions of the ambient air entering the system and a reference outlet (room) air conditions of 24 °C and 50% relative humidity (ASHRAE, 2013). In contrast, in an AMH process the desired product is the condensed water. Hence, the latent heat of condensation, which results from the phase change of the water vapor, is unavoidable while the sensible cooling of the air is the overburden. Namely, a smaller sensible heat interaction will result in a higher efficiency of the process. The ratio of the latent-to-total heat interactions is the key parameter for assessing the overall energy requirements of a moisture harvesting process by direct cooling. This ratio should be determined relative to a reference point. Clearly, the reference point for air conditioning (24 °C and 50% RH) is not useful for moisture harvesting due to the high residual moisture content at the outlet (N9 g_w/kg_a). Since lower cooling temperatures result in lower residual moisture content and higher water yield, in this study cooling of the ambient air to

4 °C, with residual moisture content of 5 g_w/kg_a, was chosen to be the reference point. Although this choice is supported by technical specifications of commercial water generators (e.g. Watair Inc., 2012) and mechanical dehumidifiers (Harriman, 2002), the following thermodynamic derivation of the MHI enables the use of any other condensation temperature.

When moist air undergoes an isobaric process, the total heat interaction equals the enthalpy difference between its inlet, i, and outlet, o, states

$$q_{tot} = h_o - h_i; \qquad (2)$$

where h [kJ/kg_a] is the specific enthalpy of the moist air. However, since the goal of the process is freshwater production, it is more useful to calculate the heat interaction of production of 1 kg_w of liquid water. This is obtained by dividing Eq. (2) by the difference of the air moisture content between the inlet and outlet states,

$$q_{tot}^{\sim} = \frac{h_o - h_i}{r_o - r_i}; \qquad (3)$$

where $q_{tot}^{\sim}$ [kJ/kg_w] is the total heat required to be removed from the air during the production of 1 kg of liquid water and r [kg_w/kg_a] is the air moisture content (mixing ratio). Assuming operation at steady state conditions, the fraction of the latent heat out of $q_{tot}^{\sim}$ for an AMH process can be calculated by dividing the enthalpy of condensation, h_{fg} [kJ/kg_w], by $q_{tot}^{\sim}$. This quotient is designated the Moisture Harvesting Index, MHI,

$$MHI = \frac{h_{fg}}{q_{tot}^{\sim}} = \frac{r_i - r_o}{h_i - h_o} h_{fg}. \qquad (4)$$

In practice, h_{fg} depends on the temperature at which phase change takes place, yet it varies only slightly for the range of condensation temperatures found in commercial AMH applications (e.g. for an increase of 1 °C in the condensation temperature h_{fg} decreases by b 0.1%). Hence, for convenience and simplicity a constant value of h_{fg} at 4 °C (2492 kJ/kg_w) is used.

As implied by Eq. (4), the MHI depends on three parameters: the thermodynamic conditions of the air at the inlet (T_i, r_i, where T_i is the ambient air dry bulb temperature) and the condensation temperature, which characterizes the saturated air leaving the evaporator, T_o (before heat recovery, see below). The condensation temperature is a design parameter. Hence, for a given device the MHI depends solely on the thermodynamic conditions of the air at the inlet, i.e. the ambient conditions. Fig. 1 depicts lines of constant MHI for a condensation temperature of T_o = 4 °C, drawn on a psychrometric chart. These lines can be used for identifying inlet conditions that represent favorable ambient conditions for a direct cooling AMH process. Specifically, MHI = 1 can be obtained only by condensation of pure water vapor. Moisture extraction by direct cooling from ambient air will always be characterized by MHI b 1. For example, MHI = 0.5 represents identical sensible and latent heat interactions. High MHI characterizes warm and very humid ambient conditions (Fig. 1), where the requirement for sensible heat removal is small and the overall efficiency of the AMH process is relatively high. In contrast, low MHI characterizes ambient conditions that lead to high demands for sensible heat removal, and to low moisture condensation yield. In particular, if the moisture content of the inlet air, r_i, is lower than the moisture content of the saturated air at the outlet conditions, r_o, namely the inlet dew point temperature is lower than the condensation temperature, water production is impossible and the MHI is set to zero.

Since the MHI represents the energy fraction that is associated with actual vapor condensation, the process efficiency can be estimated by using the average MHI over the operation period. For example, the annual average energy requirement of an AMH process can be estimated using a site-specific climate data or a time series of meteorological
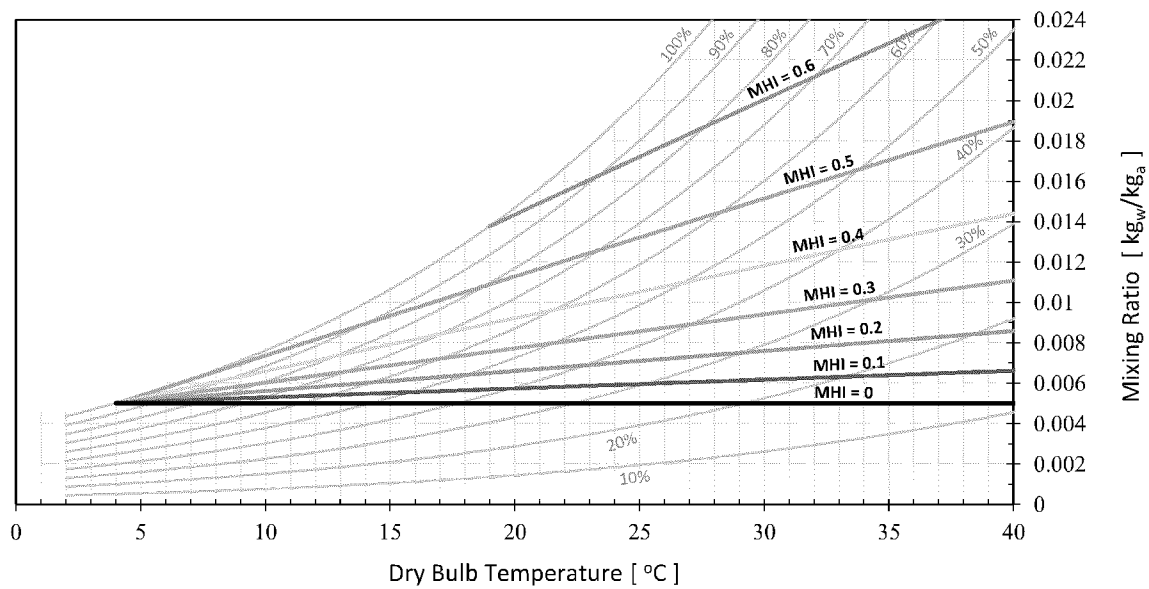
Fig. 1. Iso-MHI lines plotted on a psychrometric chart for a condensation temperature of 4 °C.

observations. The electrical power demand of the process depends on the coefficient of performance (COP, dimensionless), which is a characteristic attribute of the cooling device, representing the ratio between the heat removed from the cold reservoir and the work required to maintain the process. As such, the COP depends on the operating conditions. For an ideal system, the maximum theoretical COP is

$$COP = \frac{T_{cold}}{T_{hot} - T_{cold}} = \frac{T_{condensation}}{T_{ambient} - T_{condensation}}: \qquad (5)$$

However, the actual cooling efficiency of a system varies to a much smaller degree than the ideal Carnot efficiency, and is less influenced by small changes in the operation temperature (Wulfinghoff, 1999). Typically, common air conditioning devices are characterized by COP b 5. However, since the cold air at the outlet is not the required product of AMH systems, sensible heat recovery is possible and the cold air at the outlet can cool the inlet air, thus increasing the overall process efficiency and COP. For the sake of simplicity, we assume a fixed value of COP = 5 (Bergmair et al., 2014) when analyzing the global potential of AMH for freshwater production. Using Eqs. (3)–(5), the electrical work (kJ/kg$_w$) required for the production of 1 kg of water is

$$W = \frac{q_{tot}}{COP} = \frac{h_{fg}}{MHI \cdot COP}: \qquad (6)$$

The maximum water production rate is limited by the cooling capacity of the system, Q$_c$ [kW]. Hence, if the cooling capacity of the system is known the water production rate can be estimated to be

$$\dot{m}_w = \frac{Q_c}{q_{tot}} = \frac{Q_c \cdot MHI}{h_{fg}}; \qquad (7)$$

where $\dot{m}_w$ [kg$_w$/s] is the water production rate (assuming the system can cool the air to the condensation temperature, T$_o$, for which the MHI was calculated). The annual average energy demand and water production rate can be estimated based on Eqs. (6) and (7) using the annual average MHI or a typical MHI over the specified operation period.

3. Climate effect on atmospheric moisture harvesting

Naturally, different locations experience distinct microclimate due to their specific altitude, latitude, distance from sea, surface albedo,

vegetation cover, and other land use/land cover attributes. Historic meteorological data enable the calculation of seasonal and daily distributions of the MHI, and an average MHI over extended periods, thus facilitating long-term AMH performance prediction. Table 1 demonstrates such a calculation for locations that were indicated as suffering from water shortage (Molden, 2007), using site-specific meteorological observations over ten years (2005–2014) retrieved from NOAA Online Data Service (NOAA, 2015a). The overall suitability of each site for AMH is presented in terms of its average MHI.

Global-wise, the most suitable location for AMH from all the locations that were examined (Table 1) is Cabanatuan, the Philippines, which is characterized by a ten years average MHI of 0.59. In the following, we assume that the operation of an AMH system under ambient conditions that require twice the amount of energy for production of 1 kg of freshwater than in Cabanatuan, i.e. MHI b 0.3, is inefficient energetically, economically, and operational-wise. Hence, MHI b 0.3 represents unfavorable conditions for AMH. Consequently, the time fraction (out of the 10 years study period) that is estimated to be suitable for AMH is also shown in Table 1. T h e e f f e c t of setting other MHI-thresholds is demonstrated in Table 2 for selected sites. Fig. 2 depicts the results for a subset of the locations that appear in Table 1, overlaid on the global water scarcity map (Molden, 2007).

Together, the long term average MHI ($\overline{MHI}$), the fraction of time in which AMH is favorable, and the estimated year-round specific energy requirements for water production provide means to assess the feasibility and suitability of any location for AMH by direct cooling. Clearly, a favorable location for AMH is a site that is characterized by a considerably high $\overline{MHI}$ and a large fraction of favorable operation time. The cities of Aden, Yemen; Mombasa, Kenya; and Panjim, India, as well as other coastal cities, seem suitable for water production by means of AMH (based on the conditions set above). In contrast, non-coastal cities show varying conditions. For example, while Nairobi, Kenya, and Tiruchirapalli, India, enjoy tropical climate, which is ideal for AMH, the city of Beijing, China, experiences much dryer weather, resulting in a very low $\overline{MHI}$. Cleary, accurate site-specific meteorological conditions cannot be inferred from geographic specifications (i.e. latitude, altitude, distance from the sea), since many local factors influence the site microclimate. Nonetheless, the $\overline{MHI}$ provides a useful way to characterize meteorological-climatological conditions in terms of their suitability for AMH.

Table 1
Estimated performance of AMH by direct cooling in different locations that suffer from water scarcity. Meteorological data were obtained from NOAA (NOAA, 2015a) for the years 2005–2014. Within each country, the locations are sorted from high to low $\overline{MHI}$.

Location		Average temperature[a]	Average mixing ratio[a]	Annual rainfall	Altitude	Latitude	Distance to the sea	Average $\overline{MHI}$[b]	Favorable time (MHI N 0.3)	Energy req.[c]
Country	City	(°C)	(g/kg)	(mm)	(m)	(°)	(km)	(-)	(%)	(kWh/L)
Australia	Perth	18.4 (±6.7)	8 (±2)	867	25	- 31.94	2	0.29	52.6%	0.47
	Moree	19.4 (±7.8)	8 (±3)	595	211	- 29.47	350	0.24	42.2%	0.57
	Canberra	13.5 (±7.5)	7 (±3)	633	621	- 35.32	100	0.21	39.3%	0.64
Burkina Faso	Ouagadougou	28.6 (±5.1)	12 (±6)	792	307	12.36	800	0.32	58.9%	0.43
China	Xianyng	13.8 (±10.8)	8 (±5)	539	470	34.44	900	0.25	48.0%	0.55
	Beijing	12.9 (±11.9)	7 (±6)	577	33	40.08	170	0.19	37.0%	0.70
Egypt	Cairo	22.8 (±6.8)	10 (±4)	26	116	30.11	180	0.32	60.4%	0.43
	Aswan	27.4 (±8.5)	6 (±2)	5	200	23.95	170	0.07	1.5%	1.99
India	Panjim	27.4 (±3.2)	18 (±3)	2750	59	15.49	2	0.55	99.2%	0.24
	Tiruchirapalli	28.9 (±4.3)	16 (±2)	830	60	10.76	280	0.51	98.9%	0.27
	Rajkot	27.2 (±5.9)	14 (±6)	690	122	22.30	100	0.41	72.2%	0.33
Israel	Ashdod	21.4 (±5.4)	12 (±4)	344	17	31.80	1	0.45	88.7%	0.30
	Beit Shean	22.3 (±8.0)	10 (±3)	300	-120	32.47	50	0.35	71.5%	0.38
	Sde Boker	18.8 (±7.5)	8 (±4)	93	480	30.85	90	0.29	53.0%	0.47
	Eilat	25.9 (±8.0)	7 (±3)	22	9	29.56	1	0.15	19.1%	0.88
Kazakhstan	Aralsk	9.6 (±16.1)	5 (±3)	144	56	46.78	300	0.09	11.7%	1.48
Kenya	Mombasa	26.6 (±2.7)	17 (±2)	1050	61	- 4.04	1	0.55	100%	0.25
	Nairobi	19.5 (±3.9)	12 (±2)	1050	1623	- 1.32	250	0.45	89.2%	0.30
	Wajir	29.4 (±3.7)	14 (±2)	622	234	1.73	370	0.44	93.9%	0.31
Mali	Senou	27.6 (±5.3)	12 (±6)	959	374	12.54	450	0.33	59.1%	0.41
Morocco	Casablanka	18.5 (±4.7)	11 (±3)	426	62	33.56	1	0.46	92.6%	0.30
	Taza	19.3 (±8.6)	9 (±3)	801	510	34.22	100	0.30	58.6%	0.45
Philippines	Cabanatuan	27.3 (±3.4)	20 (±3)	2151	32	15.47	60	0.59	100%	0.23
Syria	Damascus	17.7 (±9.8)	6 (±3)	204	615	33.41	80	0.16	25.4%	0.87
USA	New Orleans	20.6 (±7.6)	12 (±5)	1613	1	29.82	1	0.41	77.9%	0.33
	Austin	20.2 (±9.2)	11 (±5)	836	141	30.26	150	0.35	69.2%	0.39
	Tucson	21.4 (±9.4)	6 (±4)	303	766	32.21	150	0.10	17.8%	1.30
Yemen	Hodeidha	29.8 (±3.9)	20 (±4)	100	12	14.75	1	0.55	99.7%	0.25
	Aden	29.2 (±3.3)	16 (±3)	30	3	12.83	1	0.50	99.2%	0.27
	Sanaa	19.0 (±5.9)	6 (±3)	200	2206	15.48	150	0.10	16.8%	1.35

[a] Standard deviation of the temperature and the mixing ratio are provided in parenthesis.
[b] MHI is calculated assuming condensation temperature of 4 °C.
[c] Energy requirements were calculated assuming COP = 5 and continuous year round operation.

4. Energy requirements of AMH and water production costs

Due to varying daily and seasonal meteorological conditions, the MHI shows considerable variability. Year-round continuous operation of an AMH device is reasonable only in tropical regions, which experience high relative humidity and stable temperatures throughout the year. Considerable decrease in energy requirements may be achieved by using time-resolved MHI for informed selection of economically advantageous operation periods, while avoiding operation of the system when the MHI is low (hence, shifting from continuous to non-continuous operation). For example, narrowing the system operation time in non-tropical regions may result in an overall lower energy requirement (per kg of freshwater produced) if the AMH process is switched off when the MHI is low. Clearly, the drawback of such an intermittent operation mode may be smaller water production and possibly mechanical problems due to the discontinuous operation cycle. This operation strategy can be implemented based on economic considerations or when apart from freshwater shortage, the energy is also limited. Fig. 3 presents the hourly MHI variation in different months at four locations, revealing distinct

Table 2
Estimates of the reduced energy requirements and water production of an AMH process under intermittent mode of operation. The applied assumptions are identical to those in Fig. 3.

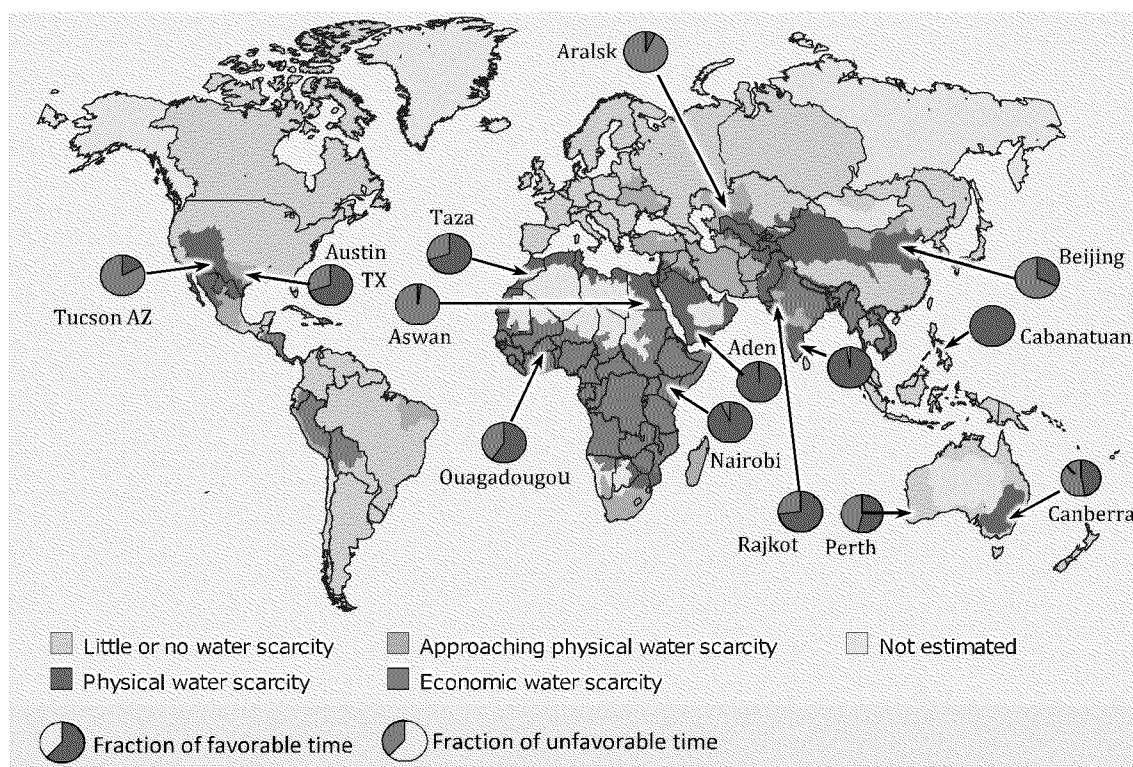| MHI threshold	Percentage of favorable operation time (%)	Average MHI during the operation hours (-)	Estimated specific energy requirement (kWh/L)	Energy saving (%)	Water production reduction (%)
Perth, Australia					
Continuous operation	100	0.29	0.47	–	–
MHI N 0.1	83	0.34	0.40	16	1
MHI N 0.2	71	0.37	0.36	23	7
MHI N 0.3	53	0.42	0.33	31	22
Sde Boker, Israel					
Continuous operation	100	0.32	0.43	–	–
MHI N 0.1	69	0.46	0.30	30	1
MHI N 0.2	64	0.48	0.28	34	3
MHI N 0.3	59	0.50	0.27	37	7
Ouagadougou, Burkina Faso					
Continuous operation	100	0.29	0.47	–	–
MHI N 0.1	73	0.39	0.35	26	1
MHI N 0.2	64	0.42	0.32	32	5
MHI N 0.3	59	0.46	0.30	37	15

Fig. 2. Fraction of the time out of the 10 years (2005–2014) meteorological data in which the ambient conditions were estimated to be suitable for AMH (e.g. MHI N 0.3), overlaid on the physical and economical global water scarcity map (adapted from Molden, 2007).

MHI patterns. Aden, Yemen, is characterized by a very large fraction of favorable time for AMH throughout the year (indicated by green and blue in Fig. 3), with very small daily and seasonal variation. Perth, Australia, is less suitable for AMH, with a more pronounced daily variation and a small seasonal variation. Ouagadougou, Burkina Faso, is characterized by a very pronounced seasonal variation, with AMH expected to be more suitable in the summer and is clearly unsuitable in the winter. The climate of Sde Boker, Israel, reveals a pattern of both seasonal and daily variation, suggesting that non-continuous operation may result in a significant reduction in energy demands and operation costs.

Daily variation of the MHI is evident in all the seasons, with higher MHI generally characterizing the night, making it the more favorable operation period (note that electricity is also cheaper at night in some locations due to lower load). Details of the energy saving can be approximated by assessing the $\overline{MHI}$ over the operation hours for different MHI thresholds (with AMH assumed to take place when MHI N MHI_{thresh}), in comparison to the overall $\overline{MHI}$ over the whole period (i.e. continuous operation). Table 2 contains estimates of energy saving that may be achieved by MHI-informed operation strategy for different MHI_{thresh}, and the related decrease in water production relative to continuous operation.

Together, Fig. 3 and Table 2 represent four typical conditions: (a) locations with almost no daily and seasonal variability of the MHI throughout the year (represented by Aden, Yemen), (b) locations with considerable daily variability but negligible seasonal variability of the MHI (represented by Perth, Australia), (c) locations with little daily variability but considerable seasonal variability of the MHI (represented by Ouagadougou, Burkina Faso), and (d) locations where considerable daily and seasonal variability of the MHI is evident (represented by Sde Boker, Israel). These four location types may benefit from distinct AMH operation modes for keeping the AMH process relatively cost-effective. Possible modes of operation include year-round continuous operation, season-specific continuous operation, time-of-the-day intermittent

operation (non-continuous daily operation), and any combination of these options.

5. Discussion

This work demonstrates that the Moisture Harvesting Index (MHI) is a useful index for screening the feasibility and cost-effectiveness of atmospheric moisture harvesting by direct cooling. Proximity to a large body of water oftentimes results in high ambient humidity, thus most coastal cities were found to be suitable for AMH, unlike many inner-continental locations. For example, Aden and Hodeida are two coastal cities in the arid country of Yemen that suffer from a severe water shortage, with b 100 mm annual rainfall. Both cities experience high $\overline{MHI}$ and a large fraction (~99%) of favorable time for AMH. In fact, the year-round low temperature of the Red Sea can possibly be used as a heat sink, replacing the electrical cooling process with a cheaper seawater-air heat exchanger. Still, at present, seawater desalination in coastal cities is clearly a cheaper alternative for fresh water production, with energy requirement of 0.0025–0.0045 kWh/L for a RO desalination process (Gude, 2015), about two orders of magnitude smaller than the values appearing in Tables 1 and 2. Thus, for AMH to be competitive with standard RO-desalination fresh water production in coastal regions new technology rather than direct cooling of the ambient air should be sought. Indeed, Bergmair et al. (2012, 2014) suggested that energy saving can be achieved by cooling only the moisture after separating it from the air by a vapor selective membrane. It is noteworthy that the MHI can be used to quantify also the amount of energy that can be saved by such a process, yet this is beyond the scope of the present work. As has been demonstrated above, a climate based screening process may be used for the selection of regions that better suit AMH. For example, inland locations in Kenya, India and the Philippines experience favorable climate for AMH (Table 1), since they are characterized by equatorial climate and experience high temperatures and relative-humidity year round. However, in non-tropical inner-continental regions the $\overline{MHI}$ is
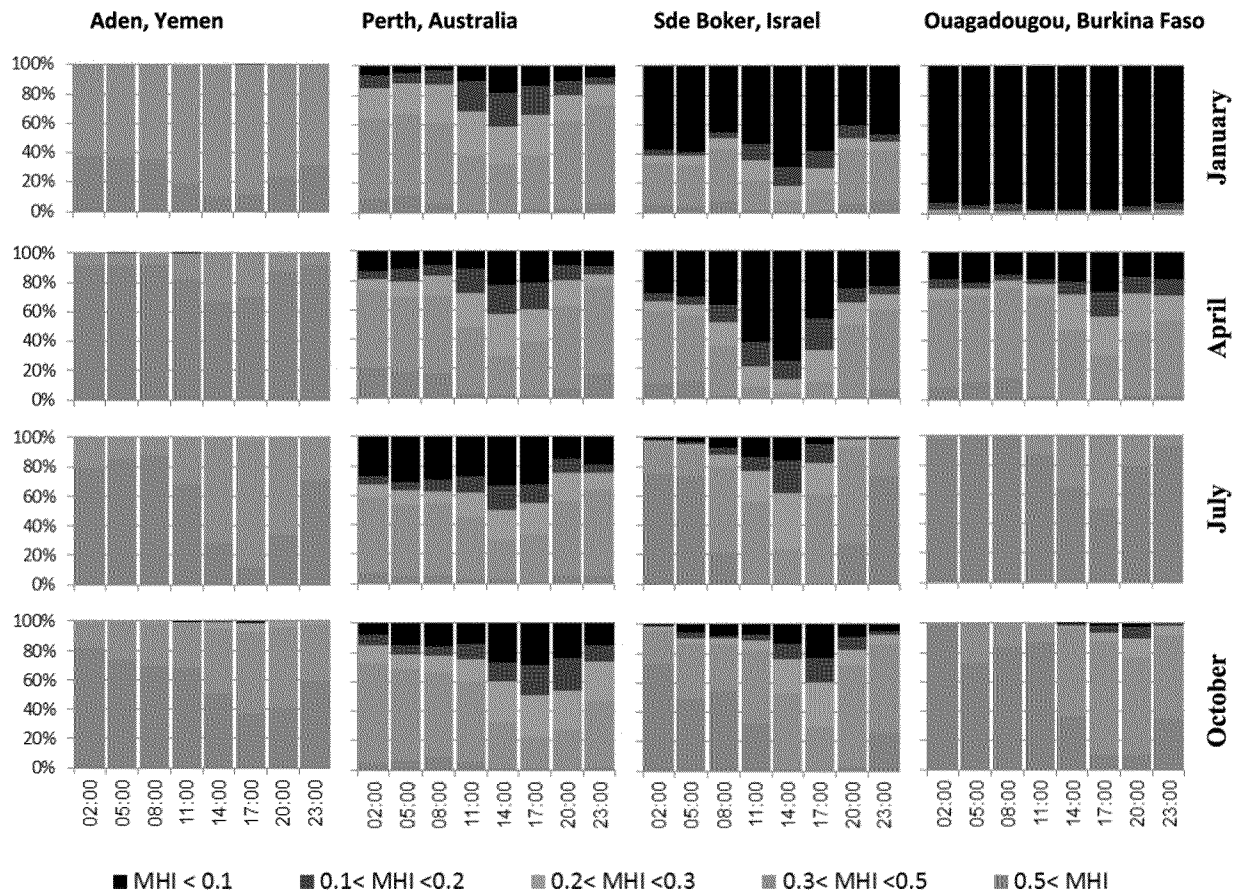
Fig. 3. Daily variation of the MHI in different seasons at four typical locations. The MHI was calculated based on 10 years (2005–2014) of climate data (NOAA, 2015a), assuming condensation temperature of 4 °C.

oftentimes low. For example, unlike Yemen's coastal climate, the climate in Sanaa, which is located in Yemen's highland, is cold and dry. This makes the city not suitable for efficient AMH, with MHI N 0.3 in only in 17% of the time. A similar effect of the topography on the local climate has been reported in western Saudi Arabia (Hamed, 2011), showing a diminishing AMH potential as the distance from the sea increases. In Israel, the AMH potential also decreases with the distance from the Mediterranean Sea, with Sde Boker, which is located 90 km to the south-east of the coastal city of Ashdod, experiencing much lower $\overline{MHI}$ and smaller fraction of favorable time for AMH than Ashdod. The African countries of Mali and Burkina Faso are good examples for countries that do not have access to the sea and therefore cannot desalinate seawater. Whereas these two sub-Saharan countries are characterized by moderate $\overline{MHI}$ (~0.33) and ~60% of the time seems to be favorable for AMH (Table 1), the seasonal variation is significant (Fig. 3). Specifically, in the dry season, around January, the high pressure subtropical belt migrates southward and AMH is clearly not favorable. Therefore, year-round operation would be energetically inefficient. Nonetheless, AMH can be a supplementary water source in the dry season in these counties. On the other hand, Austin, TX, which is an inner-continental city that is located ~150 km from the ocean and suffers from moderate to severe drought (NOAA, 2015b), seems to have suitable climate conditions for AMH. Yet, for this to mature, water production by AMH must be cheaper than conveying desalinated water from the ocean or from an underground brackish water reservoir (Wahlgren, 2014; Gude, 2015). Together, all these observations suggest that the local climate has a key role in the cost-effectiveness of AMH as an alternative water source. Moreover, in most of the surveyed locations the climatic conditions result in $\overline{MHI}$ b 0.5, suggesting that N50% of the energy invested in AMH is wasted on cooling of the air rather than on water

production. In fact, this is the major drawback of atmospheric moisture harvesting by a direct cooling process.

AMH can be competitive with RO seawater desalination only in locations where large investments in infrastructure are required, including in piping to transport the desalinated water to the consumers. For small and scattered communities with relatively little freshwater demands, a decentralized AMH may be more useful than other solutions, especially if the initial capital required to establish the infrastructure is limited. Alternatively, AMH by direct cooling may be the preferred option when the process by-product, the cooled air, has also a market, e.g. for air conditioning (Habeebullah, 2009).

6. Conclusions

The feasibility of atmospheric moisture harvesting (AMH) by direct air cooling and the energy efficiency of such a process depend on the thermodynamic state of the ambient air. The Moisture Harvesting Index (MHI) is a useful index for analyzing such a technology. AMH is expected to be more cost-effective in tropical or coastal regions that enjoy warm and humid climate. However, in such locations AMH cannot compete with simple collection of rainwater (Sharan et al., 2011). On the other hand, in dry regions that suffer from water shortage the ambient air conditions are often less favorable for AMH by direct electric cooling (low MHI) and levy high energy demands per unit water production. Hence, for AMH to be a viable resource of freshwater a different moisture harvesting process, other than direct cooling of the moist air, should be sought. Since AMH by direct cooling wastes a large portion of the energy on cooling the air, future vapor separation methods may provide a technological alternative to reduce the AMH operational costs.

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